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Breakdown Measurement of N₂O Mixtures with CO₂, N₂, O₂ in Uniform Electric Fields

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ABSTRACT

Breakdown strength in uniform electric fields of N₂O mixtures with CO₂, N₂, and O₂ is measured under AC voltage stress, 300 kPa pressure, and electrode separation of 5 mm. The obtained results show the best synergism of 115% for N₂O/CO₂ 30/70 mixture. For high electric strength of mixtures a high fraction of N₂O is beneficial, but is limited by the oxidizing power. Considering this limit a N₂O/CO₂ 49.1/50.9 mixture can be used with the electric strength 135% of synthetic air and 45% of SF₆, respectively.

Index Terms — nitrous oxide, synergism, alternative gas insulation, electric breakdown

1 INTRODUCTION

NITROUS oxide (N₂O) and its mixtures have been discussed as an environmentally friendly alternative insulating medium to SF₆ in gas insulated switchgears (GIS). N₂O is a commercially available, non-toxic (LC50 > 500 000 ppm), and non-flammable gas [1]. Anesthetic effects of N₂O like moderate analgesia start at exposure concentrations of 6% [2]. The working exposure limit is around 100 ppm [1]. The low boiling point of -88.5°C and low roughness sensitivity would allow higher operating pressures in comparison to SF₆. The roughness sensitivity is characterized by the product of gas pressure and protrusion height from which the breakdown field strength starts to drop. It is 43 MPa μm for N₂O and only 6 MPa μm for SF₆, respectively [3]. With a global warming potential (GWP) of 265 to 298 on a 100 year horizon (1.2% of SF₆) [4], N₂O would significantly reduce the environmental impact of high voltage equipment. The ozone depletion potential (ODP) of N₂O is estimated to be 0.017 [5]. The total anthropogenic emission of N₂O is estimated to be in the order of magnitude of 10 million tons per year [6], the total SF₆ amount banked in electrical equipment is in the order of magnitude of 0.1 million tons with a leakage rate of 1% per year [7]. The molar mass of N₂O is 1/3 of SF₆. Consequently the use of N₂O in electrical equipment would contribute to the total N₂O emissions with less than 0.001 million tons per year. The gas molecule number density reduced critical electric field strength $(E/N)_{crit}$ of N₂O is

reported to be pressure dependent due to three body attachment, which is also a well-known of a number of gases e.g. HFO1234ze(E) [8], C₃F₆, and C₃F₈ [9]. Figure 1 shows the results of several measurements available in literature.

Assuming application pressures of several 100 kPa, the electric strength (ES) of N₂O would be around half that of SF₆, and more than 1.6 times that of air [9-12]. However, the use of pure N₂O in applications is not considered feasible due to its oxidizing power, which is taken to be 0.6 times that of oxygen [15]. The issue is less with combustion - since there is no flammable material within the pressure vessel - but more a matter of material degradation, and rusting.

Figure 1. $(E/N)_{crit}$ of N₂O for different pressures p and 293 K. Biasutti and Zaengl [9]: calculation from breakdown experiments. Dutton *et al* [11]: calculation from breakdown experiments. Hösl *et al* [13]: Calculations based on kinetic model as Bolsig+ simulation based on the cross section set of Dupljanin *et al* [14] in combination with three-body stabilization. Replotted from [13].

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To reduce the oxidizing power, N_2O can be mixed with inert buffer gases such as N_2 , or CO_2 , which has the additional advantage of decreasing the environmental impact, by diluting N_2O and therefore reducing GWP and ODP.

Moreover, recently Hösl *et al* [13] have discussed a stabilization pass for unstable NO^- ions, created by secondary anion processes after dissociative attachment to N_2O . When impacted with an electron, N_2O readily dissociates into N_2 and O^- , which is the only relevant attachment channel. Subsequently, O^- interacting with a neutral N_2O may, at high pressures, be stabilized as a $N_2O_2^-$ anion, which is presumably stable at relevant energies. This stabilization competes with the immediate decay of $N_2O_2^-$, resulting in an NO^- anion. This anion undergoes rapid electron detachment if not stabilized by further processes. This stabilization can be greatly enhanced by the addition of O_2 (Equation (1)) and CO_2 (Equation (2)), leading to a stable CO_4^- .

This kind of stabilization might increase the ES of the mixture and might lead to synergism (if ES of the mixed components is better than their linear combination) or even positive synergism (if ES of the mixed components is above that of each of the components) [13]. The beneficial behavior of mixtures of N_2O with CO_2 , N_2 , and O_2 has been presented by N. Hayakawa *et al* [16], and by H. Kojima *et al* [17] for impulse voltages. At 100 kPa pressure, improvements for the 50%-breakdown probability in comparison to pure N_2O could be achieved up to 35% for negative, and up to 25% for positive impulse polarity. W. Pfeiffer and D. Schoen [18] reported for very fast overvoltage stress that 20/80 and 40/60 N_2O/N_2 mixtures can achieve at 700 kPa up to 90% of SF_6 breakdown strength. For 100 kPa however, the performance was only slightly above N_2 corresponding to 60% of SF_6 . M. Akbar and N. Malik [10] measured a synergy in N_2O/CO_2 for DC voltage. Th. Hammer and T. Kishimoto [19] investigated plasma-chemical decomposition of N_2O/N_2 40/60 mixture and concluded that no degradation of ES can be expected.

The above listed investigations show that the kinetic processes of N_2O and its mixtures, and consequently its ES might be pressure dependent. Consequently, low pressure measurements in swarm experiments might not be sufficient to represent the ES at application pressures. Further, there is a lack of data describing the ES of ternary N_2O -mixtures under uniform field stress and slowly increasing voltages.

The goal of the breakdown measurements presented in this publication is to identify if there is a mixture of N_2O with CO_2 , N_2 , and O_2 at typical operating pressures with a beneficial ES in comparison to pure N_2O under uniform field and AC voltage stress. The article is structured as follows: Section 2 describes the experimental setup, Section 3 the evaluation methods, Section 4 shows the breakdown measurement result, Section 5 discusses the results with focus on synergism and oxidizing power of mixtures, and Section 6 gives a conclusion.

2 EXPERIMENTAL METHODS

The experimental breakdown setup of the high voltage laboratory of ETH Zurich, previously described in [20], is shown in Figure 2. For the AC high-voltage circuit, standard components of the Messwandler-Bau Bamberg (MWB) construction kit are used. The AC voltage is provided by a control unit containing a frequency converter with a filter [21]. The control unit can automatically execute the experimental sequence with settings of maximal voltage, voltage rate of rise, number of repetitions, and waiting time between consecutive voltage applications. A breakdown detection feedback loop turns off the voltage within 30 ms to limit the discharge energy and decrease the stress on the gas under investigation and on the electrode surface. In addition, the energy dissipated in the discharge spark is limited by two series-connected 50 k Ω resistors. The voltage is measured by a capacitive divider and a MU17 HIGHVOLT unit saving the sine voltage peak before the breakdown. The overall voltage measurement accuracy is better than 2%. In order to reduce the statistical time lag, the AC voltage rate of rise before breakdown is 0.1 kV/s. To have a reasonable low experimental time, the rate of rise is 2 kV/s up to 80% of the estimated breakdown voltage.

The gas is stressed with a uniform electric field created by two plane electrodes with a Rogowski shaped edge profile. The plane electrodes provide a large stressed volume in comparison to sphere arrangements and reduce the statistical time lag this way. The stainless steel (EN 1.4460) electrodes have a total diameter of 80 mm with a flat area diameter of 40 mm and ensure a uniform field up to 15 mm separation distance.

The electrode finish is polished with fine sandpaper. Measurements with a contact profilometer (JENOPTIK HOMMEL-ETAMIC TURBO WAVE) delivered a roughness of $R_t = 1.3 \mu m$, with R_t defined as difference between the highest peak and deepest valley measured on a path of 4.8 mm along the electrode surface. We estimate a more conservative roughness of $R_t = 3 \mu m$.

For the present investigations an electrode separation of 5 mm is used. The electrodes are supported by a polypropylene (PP) tube placed inside the pressure vessel to decouple them mechanically from the outer vessel and ensure a pressure-independent separation. The temperature-dependent change of the electrode separation, due to the thermal expansion of the PP-tube, was measured for a temperature range from 20°C to 27°C. A linear approximation delivers a separation change of 48.37 $\mu m/K$, which is considered in the data evaluation for E/N .

The electrodes are aligned parallel by three bolts connecting the upper electrode to a holding plate. The necessary counterforce is generated by stiff springs around the bolts. The separation and the alignment is set using gauge blocks available in 1000 μm , 100 μm , 10 μm , and 1 μm step size. Trials with using different step sizes and fine electrodes readjustment showed a separation accuracy estimated to be $\pm 80 \mu m$, and the parallelism $\pm 5 \mu m$. The good parallelism and uniform electric field distribution are confirmed by the uniform distribution of breakdown spark roots over the flat electrode area after the

experiments. The field uniformity at the flat area, where the breakdown sparks took place, is considered to be 100%. As if a field enhancement would appear on Rogowski-electrodes, then it would be around the edges leading to spark root concentration in this region.

Figure 2. Schematics of the experimental setup with breakdown circuit and pressure vessel.

The gases are filled and mixed directly in the experimental vessel which is made of glass-fiber reinforced epoxy with 11.5 L volume, designed for a maximal pressure of 900 kPa. A good mixing of components is ensured by a fan inside the vessel. The fan with 2 cm stilts placed on the floor of the vessel, creates a flow direction from the bottom to the top. The mixing time was > 20 min. The indicated percentage of mixtures is related to their partial pressures during filling. Pressure and temperature are measured by a WIKA CPG1500 sensor with a pressure accuracy ≤ 0.6 kPa (6 mbar) and estimated temperature accuracy ≤ 1 K.

In each gas mixture 50 to 250 breakdowns are performed. For each breakdown pressure and temperature is recorded. The time between two consecutive breakdowns is around 4 min.

3 EVALUATION METHODS

3.1 PERCENTILES CALCULATION

A breakdown is a statistical process. For a uniform field at least two criteria have to be fulfilled: the electric field strength has to be high enough to fulfill the ignition criterion for Townsend or streamer mechanism, and a seed electron has to be available to start the breakdown process. The distribution of breakdown values is not necessarily normal, so a binominal distribution is used for the evaluation. The results are presented as median with 84.13 and 15.87 percentiles with 75% of confidence according to [22]. The corresponding values can be calculated according to Equation (3) ordering the breakdown voltages in an increasing order to a list with samples x_i , $i = 1 \dots n$, with total breakdown number n , and $1 \leq m \leq n/2$, where m is any integer. P_{prc} is the point below which a certain percentage of the measured points lie, prc is a certain percentile of distribution. $P\{\}$ is the confidence of the percentile. k is a running number for the sum calculation. The binomial coefficient is calculated with Equation (4). For the evaluation we use $P\{x_m \leq P_{15.87}\} = 0.75$. The example for different

sample sizes are shown in Table 1. The example of breakdown values sorted to increasing order with highlighted percentiles is shown in Figure 3.

$$P\{x_m \leq P_{prc}\} = P\{x_{n-m+1} > P_{1-prc}\} = 1 - \sum_{k=0}^{m-1} \binom{n}{k} prc^k (1-prc)^{n-k} \quad (3)$$

$$\binom{n}{k} = \frac{n!}{k! \cdot (n-k)!} \quad (4)$$

For a normal distribution, the median will correspond to the mean, and the 84.13 and 15.87 percentiles to median plus and minus the standard deviation, respectively.

Table 1. Percentile values i for different sample sizes n .

Total breakdown number n	value i of percentiles for 75% confidence $P\{\}$	
	prc 15.87 %	$1-prc$ 84.13 %
5	-	-
10	1	10
20	2	29
30	3	28
50	6	45
100	13	88
150	16	135
200	28	173
250	36	215

Figure 3. Example distribution of breakdowns sorted by increasing values with indications of median and confidence intervals for 50/50 N_2O/CO_2 .

3.2 E/N CALCULATION

$(E/N)_{crit}$, defined as E/N value where the corresponding effective ionization rate is zero, can be obtained with swarm experiments under low pressures (typically $<< 10$ kPa). Measurements at operating pressures in breakdown experiments with uniform field stress, deliver the gas molecule number density reduced breakdown field strength $(E/N)_{bd}$, which is above $(E/N)_{crit}$. With increasing product of gas pressure and electrode separation ps , $(E/N)_{bd}$ converges to $(E/N)_{crit}$. For high ps values $(E/N)_{bd} \approx (E/N)_{crit}$ is valid [3]. $(E/N)_{bd}$ enables to compare the breakdown voltages U_{bd} in uniform field stress under different experimental conditions like electrode separation s , pressure p (in Pa) and temperature T (in K). Assuming the ideal gas law, $(E/N)_{bd}$ can be calculated according

to Equation (5). Its unit is Townsend ($1 \text{ Td} = 10^{-21} \cdot \text{V} \cdot \text{m}^2$). k_B is the Boltzmann constant.

$$\left(\frac{E}{N}\right)_{\text{bd}} = \frac{U_{\text{bd}} / s}{p / (k_B \cdot T)} \quad (5)$$

The temperature-dependent change of the electrode separation is also considered for each breakdown with Equation (6), taking into account the separation s_{init} and temperature T_{init} during separation setting.

$$s = s_{\text{init}} + 48.37 \frac{\mu\text{m}}{\text{K}} \cdot (T - T_{\text{init}}) \quad (6)$$

The overall accuracy of $(E/N)_{\text{bd}}$ value is supposed to be better than 7%, which is due to the uncertainties of separation setting, and measurements of temperature, pressure, and voltage.

3.3 SYNERGISM CALCULATION

A possible beneficial effect of using a gas mixture is that its $(E/N)_{\text{cirt}}$ and consequently $(E/N)_{\text{bd}}$ may exceed the linear combination of the partial components weighted by their molar fraction ($\text{mol}\%$). The synergism coefficient (SC) can be calculated according to Equation (7) for n components. If $SC > 100\%$, we can talk about synergism. If in addition $(E/N)_{\text{bd,mixture}} > (E/N)_{\text{bd,comp } x}$ is valid for all components x in pure state, we can talk about positive synergism [23].

$$SC = \frac{(E/N)_{\text{bd,mixture}}}{\sum_{x=1}^n [\text{mol}\%_{\text{comp } x} \cdot (E/N)_{\text{bd,comp } x}]} \quad (7)$$

3.4 OXIDIZING POWER CALCULATION

According to EN-ISO-10156 the oxidizing power (OP) of a gas mixture is given in relation to pure oxygen. OP of O_2 is consequently 100%. A gas mixture is classified as oxidizing if its OP is above 23.5%. OP can be calculated as molar fraction ($\text{mol}\%$) weighted with ratio of oxygen (OE) and nitrogen equivalencies (NE) of the mixed components. OE of O_2 is 1.0, OE of N_2O is 0.6. NE of N_2 is 1.0 and NE of CO_2 is 1.5. With these data the OP of the investigated mixtures can be calculated with Equation (8).

$$OP = \frac{\sum [\text{mol}\%_{\text{oxidizing comp } x} \cdot OE_{\text{oxidizing comp } x}]}{\sum \text{mol}\%_{\text{oxidizing comp } x} + \sum [\text{mol}\%_{\text{inert comp } x} \cdot NE_{\text{inert comp } x}]} \quad (8)$$

$$= \frac{\text{mol}\%_{\text{N}_2\text{O}} \cdot 0.6 + \text{mol}\%_{\text{O}_2} \cdot 1.0}{\text{mol}\%_{\text{N}_2\text{O}} + \text{mol}\%_{\text{O}_2} + \text{mol}\%_{\text{CO}_2} \cdot 1.5 + \text{mol}\%_{\text{N}_2} \cdot 1.0}$$

4 RESULTS

In this manuscript four sets of experiments were conducted. First, breakdown experiments were performed on individual gases such as CO_2 and N_2O . Then to analyze the effect of gas mixtures as mentioned in earlier sections, breakdown experiments were conducted on binary mixtures of N_2O with N_2 , CO_2 , and O_2 at 300 kPa with an electrode separation of 5 mm. Similarly, another set of measurements were performed on ternary mixtures of $\text{N}_2\text{O}/\text{CO}_2/\text{O}_2$, and $\text{N}_2\text{O}/\text{CO}_2/\text{N}_2$. Finally, the experiments were expanded to quaternary mixtures of $\text{N}_2\text{O}/\text{CO}_2/\text{N}_2/\text{O}_2$. The results of the various experiments are plotted as described in the following paragraphs.

Figures 4 to 8 show the breakdown results as median with 15.87 and 84.13 percentiles with 75% of confidence, for the electrode separation of 5 mm.

Figure 4 shows a pressure scan for pure N_2O , CO_2 , and a $\text{N}_2\text{O}/\text{CO}_2$ 38/62 mixture. This mixture has a N_2O fraction around the maximal possible amounts for mixing with N_2 and CO_2 to have same OP as air (compare discussion in section 5). Figure 4a shows the breakdown voltages U_{bd} and Figure 4b the same values represented as $(E/N)_{\text{bd}}$. It can be observed that N_2O has a breakdown strength of 1.75 times as that of CO_2 .

Figure 4. AC peak (a) breakdown voltage U_{bd} and (b) gas molecule number density reduced breakdown field strength $(E/N)_{\text{bd}}$ of N_2O , CO_2 , and a $\text{N}_2\text{O}/\text{CO}_2$ for 5 mm separation and different pressures.

Figure 5. AC peak gas molecule number density reduced breakdown field strength $(E/N)_{bd}$ of binary mixtures of N_2O with N_2 , CO_2 , and O_2 . Electrode separation 5 mm, gas pressure 300 kPa. Black lines indicate breakdown field strength of N_2/O_2 80/20. Black solid line: median, dashed lines: percentiles.

Figure 5 shows results of the breakdown experiment performed on binary mixtures of N_2O with N_2 , CO_2 , and O_2 at 300 kPa. Similarly, Figure 6 shows the results of breakdown experiments on ternary mixtures at 300 kPa of $N_2O/CO_2/O_2$, and Figure 7 $N_2O/CO_2/N_2$. Figure 5 to 7 show an increasing trend in breakdown strength with increase in N_2O content in the mixtures.

Figure 8 shows $(E/N)_{bd}$ values of some quaternary mixtures with mixing ratios according to [17].

Figure 6. AC peak gas molecule number density reduced breakdown field strength $(E/N)_{bd}$ of ternary $N_2O/CO_2/O_2$ mixtures. Electrode separation 5 mm, gas pressure 300 kPa.

Figure 7. AC peak gas molecule number density reduced breakdown field strength $(E/N)_{bd}$ of ternary $N_2O/CO_2/N_2$ mixtures. Electrode separation 5 mm, gas pressure 300 kPa.

Figure 8. AC peak gas molecule number density reduced breakdown field strength $(E/N)_{bd}$ of quaternary $N_2O/CO_2/N_2/O_2$ mixtures. Electrode separation 5 mm, gas pressure 300 kPa.

5 DISCUSSION

In this section, the results of the breakdown experiments are compared with similar studies available in literature. Furthermore, the synergistic effects of the gas mixtures along with its oxidizing power for practical applications is discussed.

5.1 COMPARISON OF ELECTRIC STRENGTH WITH LITERATURE

For the discussion the data are compared in Figure 9 with data available in literature. Figure 9b shows buffer gases measured by P. Haeffliger [20, 24] under similar experimental conditions, but with sandblasted electrodes. While the difference between the 15.87 and 84.13 percentiles of P. Haeffliger is below 5 Td (not visible in the figure), the results of the present study show a scattering of around 10 Td. The median values are around 10 Td above Haeffliger's. This might be related to the increased statistical time lag due to the polished electrodes and the lower electron emission rate from the cathode surface in comparison to the sandblasted version. But also a relation to measurement accuracy of voltage, pressure, temperature and electrode distance cannot be excluded. We assume the 15.87 percentile to be more significant than the median to characterize the ES in the present study. This value is used to calculate synergism.

Figure 9a shows the comparison of breakdown measurements in pure N_2O . A pressure dependence of ES of N_2O cannot be observed. It has to be taken into account that in the current study the measurements were performed with changing the pressure only, while in literature in addition to pressure also the spacing has been changed to have the same ps under different pressures. In the current study the $(E/N)_{bd}$ decrease due to increasing ps may be more dominant than its increase with pressure. The measured ES between 185 and 190 Td are slightly above the literature values at similar pressure, but in the range of the estimated experimental error.

The synergism of N_2O/CO_2 mixtures agrees with [10] and [16] as shown in Figure 10a. There is no further synergism increase with admixture of oxygen as assumed in [13] and reported for 100 kPa in [16]. A possible reason might be the increased pressure of 300 kPa leading to saturation of some ion kinetic processes, notably the primary three-body stabilization of O^- , drying out the NO^- path altogether.

Figure 9. $(E/N)_{bd}$ and $(E/p)_{bd}$ at 20°C for (a) N_2O and (b) buffer gases. Akbar and Malik [10]: polished plane electrodes out of steel with Harrison profile and distance from 2 mm to 20 mm. Biasutti and Zaengl [9]: polished plane electrodes out of steel with Rogowski profile and distance up to 20 mm. Dutton *et al* [11]: silver plated plane electrodes with Bruce profile. Haeffliger [20, 24]: similar electrode geometry as in current study but sandblasted.

The good performance with admixtures of N_2 , and for quaternary mixtures measured in [16, 17] for 100 kPa with impulse voltage, is not observed in the current study with 300 kPa and AC voltage stress.

As was shown in [20, 24] it might be not sufficient to compare gas mixtures at only one ps value as $(E/N)_{bd}$ decrease with increasing ps . The resulting Paschen's curves might intersect. So a gas mixture which seems to be slightly beneficial at low ps values, might be unfavorable at higher ps values. This behavior may be significant for gases with small deviations in $(E/N)_{bd}$ like for air and mixtures with small N_2O fraction. For significant large difference in $(E/N)_{bd}$ of 20 Td and more, like between air and mixtures with more than 20% N_2O this phenomena should not play a role.

Further it has also to be considered that for gases with pressure dependent $(E/N)_{crit}$ due to three body attachment, swarm parameter measurements at low pressures are not sufficient for the characterization of the gas. In addition measurements at real application pressures, or physical models for extrapolation toward higher pressures are necessary.

5.2 SYNERGISM

For all investigated mixtures no strong synergism can be observed (Figures 10a to 12a). The best synergism values of around 115% are observed for N_2O/CO_2 fractions around 30%. For N_2O/N_2 the synergism is poor by reaching 105%. For N_2O/O_2 no synergism can be observed.

The performance of ternary $N_2O/CO_2/O_2$ as well as of $N_2O/CO_2/N_2$ mixtures is similar to N_2O/CO_2 , and decreases with the dominance of O_2 and N_2 fraction, respectively. The performance of quaternary $N_2O/CO_2/N_2/O_2$ mixtures seems to depend mainly on N_2O fraction and not on the variation of other components.

Figure 10. Comparison of (a) synergism and (b) oxidizing power of binary mixtures. Akbar and Malik [10]: polished plane electrodes with Harrison profile, 30 to 100 kPa, DC. Hayakawa *et al* [16]: polished sphere (diameter 50 mm)-plane with separation of 10 mm, 100 kPa, AC. Present study: Plane-plane Rogowski profiled electrodes, separation 5 mm, 300 kPa, AC. Black line indicates the oxidizing power limit of 23.5%.

5.3 OXIDIZING POWER

The oxidizing power sets a limit of N_2O and O_2 fractions for applications in equipment. The limit of 23.5% is indicated in Figures 10b to 12b by the black solid line. The use of pure N_2O as well as its mixtures with O_2 is not possible, while the addition of N_2 or CO_2 creates applicable mixtures. The *OP* of air (20% for O_2/N_2 20/80) can be reached with N_2O/N_2 33.3/66.7 and N_2O/CO_2 42.8/57.2 mixtures. According to this study, the *ES* of these mixtures would be 12% and 32% superior to synthetic air, respectively. The fraction of N_2O can be increased even further to N_2O/CO_2 49.1/50.9 by going to the 23.5% *OP* limit.

Figure 11. Comparison of (a) synergism and (b) oxidizing power of ternary $N_2O/CO_2/O_2$ mixtures. Hay. [16]: polished sphere (diameter 50 mm)-plane with separation of 10 mm, 100 kPa, AC. Present study: Plane-plane Rogowski profiled electrodes, separation 5 mm, 300 kPa, AC. Black line indicates the oxidizing power limit of 23.5%.

Figure 12. Comparison of (a) synergism and (b) oxidizing power of ternary N₂O/CO₂/N₂ mixtures. Present study: Plane-plane Rogowski profiled electrodes, separation 5 mm, 300 kPa, AC. Black line indicates the oxidizing power limit of 23.5%.

6 CONCLUSIONS

The ES of mixtures of N₂O with CO₂, N₂, and O₂ has been investigated under uniform electric field stress with AC breakdown experiments. At pressure of 300 kPa and separation of 5 mm a slight but no strong synergism has been observed. Consequently, a high N₂O fraction is beneficial for the ES, but limited by the oxidizing power, considered acceptable in high voltage equipment. Mixtures of 20% of N₂O with inert buffer gases N₂ or CO₂ show an ES 16% to 22% above that of synthetic air. As the *OP* of N₂O is lower than of O₂, the N₂O fraction can be increased further up to N₂O/CO₂ 49.1/50.9 showing an ES 35% higher than synthetic air, and 45% of SF₆.

For the design of a possible mixture for application, real GIS arrangements with operational pressures under AC and impulse voltage stress should be investigated.

In case of an application, N₂O concentration around the equipment would have to be monitored to avoid concentrations causing even smallest anesthetic effects (>6%), and to follow the exposure limits directions.

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